5. Molecular Gas in Nuclei of Galaxies

MOLECULAR GAS IN LUMINOUS GALACTIC NUCLEI

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Abstract
In the last five years, millimeter-wave interferometry has clearly shown the existence of enormous masses ($10^9 - 10^{10}\,M_\odot$) of molecular gas concentrated in the nuclear regions ($R < 500\,\mathrm{pc}$) of many luminous and ultra-luminous infrared galaxies. In these systems, molecular gas is an obvious source of fuel for nuclear starbursts and active galactic nuclei (AGN). For nearer, lower-luminosity systems there exists less systematic characterization of either the properties or the structure of the nuclear gas. Here we review recent results on the molecular gas in the nuclei of two near, lower-luminosity systems (M51 and NGC 1068) and contrast these results with those for the best studied ultra-luminous IRAS galaxy, Arp 220. For all three galaxies, there now exists CO(2–1) interferometry at high resolution which reveals, for the first time, disks of extremely dense, highly excited gas on scales of 50-300 pc. These structures vary in their levels of axisymmetry, thickness, and clumpiness. However, they share the ability to extinguish optical and near-infrared emission from active or stellar nuclei and perhaps to collimate radio jets and ionized outflows. Within the nuclear regions of these three galaxies, the molecular gas constitutes 10-50% of the total mass, with the most luminous systems having the highest gas mass-fractions.

1. Introduction

The critical role played by dense molecular gas in the activity of galactic nuclei has been appreciated only in the last decade. This gas, which is virtually undetectable via 21 cm HI observations (except in rare cases of absorption), has now been studied at millimeter wavelengths by both single dishes and aperture synthesis, the latter achieving $\leq 1''$ resolution in recent work. Molecular line observations have revealed masses of interstellar gas typically 10-100 times those previously inferred from 21 cm observations, a

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fact which is not a surprise if one considers the relatively large abundance of molecules in the nucleus of the Galaxy. However, despite some similarities with the nucleus of the Galaxy, higher-luminosity galactic nuclei can harbor molecular gas with quite different properties, notably a higher density (as evidenced by the relatively strong high dipole moment molecular line emission) and a structure which is continuous and disk-like (rather than clumped in discrete, self-gravitating GMCs).

In the more luminous systems, the large masses of molecular gas are undoubtedly responsible for the prodigious starburst activity and very likely responsible for feeding mass into central, pc-scale AGN accretion disks. The gas is important not only because it can form stars; it is also extremely dissipative and efficient in radiating bulk rotational energy and transfering angular momentum to larger radii. Despite its energetic environment, the molecular gas probably remains at temperatures of less than 100 K due to extremely effective cooling in molecular lines and the associated dust continuum. The bulk of the far-infrared luminosity can be characterized by color temperatures 40-80 K, and the masses of dust derived from the far-infrared opacity are consistent with the molecular gas masses assuming reasonably standard gas-to-dust abundance ratios (100-500 by mass).

In the following review, we concentrate on recent high-resolution observations of three galactic nuclei: M51, NGC 1068, and Arp 220. These three are chosen because they comprise a sequence of increasing nuclear luminosity and presumably increasing activity, and because recent studies of these systems have yielded the highest possible spatial resolution. Despite their varying luminosities and gas masses (both ranging over factors of 10^3), they exhibit strong similarities in their molecular morphologies– specifically, nuclear disks with radii 50-300 pc. Although it is unlikely that they represent an evolutionary sequence, it is clear in each case that the dense interstellar gas is a prime ingredient in and determinant of the nuclear activity.

2. M51

M51 is one of the nearest galaxies (at 9.6 Mpc, $1'' = 47$ pc) with clear, low-level nuclear activity. A point-like nuclear radio source is seen with a bipolar jet (Crane and van der Hulst 1992), and optical spectroscopy reveals narrow emission lines in the two radio lobes extending out to approximately $10''$ radius (Cecil 1988). In addition, imaging with the HST reveals X-shaped dust lanes centered on the nucleus extending to $1''$ radius (Ford 1993). 3 mm CO and HCN emission has been mapped in the central region of M51 by Kohno *et al.* (1996) and Helfer and Blitz (1997) at $4''$ and $7''$ resolution respectively. Both molecular line studies show red- and blue-shifted emission straddling the radio jet at approximately the same position

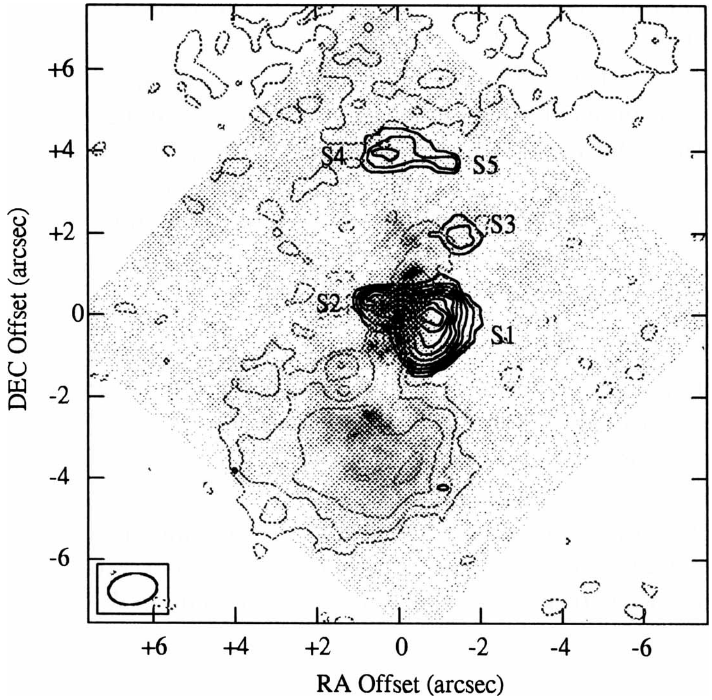

Figure 1. The integrated CO(2–1) emission (heavy contours) from Scoville *et al.* (1997a) and 6 cm radio continuum (light contours) from Crane and van der Hulst (1992) are shown superimposed on the HST Hα image (Ford *et al.* 1997) for the nucleus of M51. The CO emission was integrated over all channels containing significant line emission ($400 - 620\,\mathrm{km\,s^{-1}}$), and the contours are at 10% of the peak.

angle as the more opaque arm of the "X."

Recently, Scoville *et al.* (1997a) have obtained $1''$ resolution images of the CO(2–1) emission. In Figure 1, the total CO(2–1) emission integrated over the central $220\,\mathrm{km\,s^{-1}}$ is shown superimposed on the HST Hα image (Ford *et al.* 1997) and the 6 cm radio continuum (Crane and van der Hulst 1992). CO emission is extended with a major axis radius of 31 pc. The emission is clearly resolved since the individual velocity channel maps show a systematic shift in the emission velocity centroid.

The peak flux in the narrow band channel maps implies a beam-averaged brightness temperature of 5.1 K at 1.3 mm. Assuming a standard galactic CO-to-H_2 conversion ratio, the molecular gas mass at $R < 70$ pc is $7.7 \times 10^6\,M_\odot$. If the observed kinematic gradient is interpreted as an edge-on disk (i.e. no inclination correction), then the implied dynamical mass for the same region is $3 \times 10^8\,M_\odot$. The beam-averaged gas density within the central region is approximately $8000\,\mathrm{cm}^{-3}$ assuming filling factor ≥ 0.1 in the beam. ¿From the observed linewidth in the central beam, the mass interior to 47 pc radius is $2 \times 10^8\,\mathrm{M}_\odot$.

The location of the CO emission along the side of the radio jet suggests that the dense molecular gas may collimate the jet along an axis perpendicular to the orbital plane of the molecules. The pressure of the radio jet has been estimated to be $\sim 10^{-9}\,\mathrm{dyn\,cm}^{-2}$ (Crane and van der Hulst 1992), and for molecular gas at 50 K, the density required for equilibrium with this pressure is $\sim 10^5\,\mathrm{cm}^{-3}$. This density requirement is not very different from the beam-averaged gas density estimated above, and densities approaching $10^5\,\mathrm{cm}^{-3}$ are consistent with the relatively strong HCN emission (Kohno *et al.* 1996; Helfer and Blitz 1997). The high densities seen in the molecular gas are not in fact surprising; they may be inevitable if the density is to be sufficient to bind the molecular gas structures against tidal shear. In M51 at 50 pc radius, tidal stability requires that the gas have density of approximately $2 \times 10^4\mathrm{cm}^{-3}$.

The picture of a symmetric nuclear disk feeding mass to the central AGN of M51 is certainly oversimplified, given the asymmetry of the molecular gas structure with respect to the central radio source. Within the central $2''$, approximately three times as much CO(2–1) emission is seen on the west as on the east. At somewhat larger radii, the HCN maps by Kohno *et al.* (1996) show much greater symmetry with respect to the nucleus, and we expect that future millimeter-wave mapping with more complete *u-v* coverage at both high and low resolution will be needed to resolve this issue.

3. NGC 1068

At a distance of 14.4 Mpc, NGC 1068 is the nearest example of a bright Seyfert 2 galaxy with abundant nuclear molecular gas. Encircling the nucleus at approximately $12''$ radius are two molecular spiral arms which appear to originate from the ends of the stellar bar seen in the near-infrared (Planesas *et al.* 1991; Kaneko *et al.* 1992; Helfer and Blitz 1995). In addition, molecular gas is seen in the nucleus at $\leq 2''$ radius– weakly in CO(1-0) emission (Planesas *et al.* 1991) but much more strongly in high dipole moment molecules such as HCN (Tacconi *et al.* 1994) and in CO(2–1) (Tacconi 1998; Baker and Scoville 1997).

In Figure 2, channel maps of the CO(2–1) emission in the nucleus (Baker and Scoville 1997) are shown for velocities $\pm 73\,\mathrm{km\,s}^{-1}$ with respect to systemic. The emission is clearly elongated with a major axis approximately east-west. Channel maps further into the line wings reveal that the gas has a kinematic major axis with PA $\sim 125°$. The alignment of the kinematic

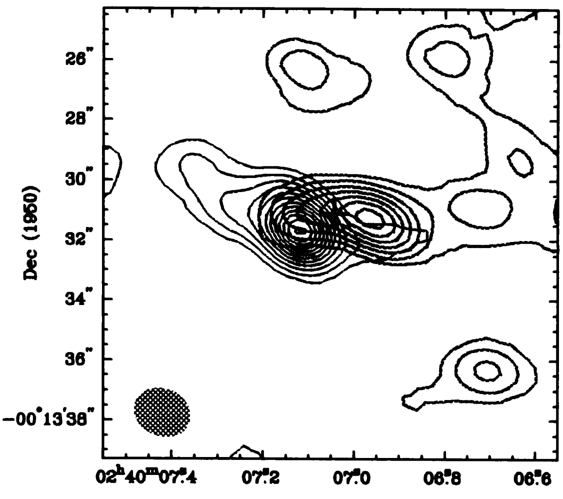

Figure 2. CO(2–1) emission from the red and blue sides of the line in the nucleus of NGC 1068 is indicated by thick and thin contours, respectively. Contour levels are multiples of 1.9 Jy bm^{-1} km s^{-1}. The position of the peak 1 mm radio continuum is shown as a cross.

major axis within 35° of the isophotal major axis suggests that the emission comes from a rotating disk, centered on the nuclear radio source (indicated by the cross). The position angle of the radio jet is approximately 25°, i.e. not far from the minor axis of the molecular gas disk. The observed morphology can be interpreted as a warped disk (Baker and Scoville 1997), although other models are possible; Tacconi *et al.* (1994) suggest inflow along a bar.

The maximum observed brightness temperature in the CO(2–1) line is 7 K, indicating a large filling factor for the gas if its true excitation temperature is $\sim$ 50 K. For a standard Galactic CO-to-H_2 conversion ratio, the molecular gas mass is $8 \times 10^7\,M_\odot$. On the other hand, the gas clearly has high excitation since the observed CO(2–1)/(1–0) brightness temperature ratio is $\sim 2-3$, well in excess of 0.8, the ratio typically seen in Galactic molecular clouds. The minimum molecular mass assuming the lines are optically thin is $\sim 3 \times 10^6\,M_\odot$ (Baker and Scoville 1997). The dynamical mass estimated from the CO(2–1) kinematics is $\sim 6 \times 10^8\,M_\odot$ within $R <$ 90 pc.

4. Arp 220

Arp 220 is the prototypical, ultra-luminous infrared galaxy with a luminosity at 8-1000 μm of $1.5 \times 10^{12}\,L_\odot$, clearly placing it in the luminosity regime of quasars. In the visual, Arp 220 exhibits two faint tails which are probably the result of a past tidal interaction (cf. Joseph and Wright 1985), and in the nucleus, high-resolution near-infrared and radio imaging reveals a double nucleus with a spatial separation of 0.95″ (Graham *et al.* 1990; Norris 1988). The projected separation of the nuclei corresponds to 330 pc; this double nucleus structure, together with the extended optical tails, suggests that the galaxy is in the final stage of galactic merging.

Single-dish observations of the CO in Arp 220 have revealed an extraordinarily high CO luminosity, corresponding to an H_2 mass of $2 \times 10^{10}\,M_{\odot}$ assuming a Galactic conversion ratio (Sanders *et al.* 1991), and 3 mm aperture synthesis has revealed that the bulk of this CO luminosity originates from the central kpc (Scoville *et al.* 1991). Recently, this system has been mapped in CO(2–1) at 1″ resolution (Scoville *et al.* 1997b; Downes 1998). This new work reveals for the first time multiple components in the dense gas: peaks corresponding to each of the double nuclei (separated by 0.95″ at PA = 101°), and a more extended disk-like structure at PA = 53° similar to the dust lane seen in optical images. Approximately two-thirds of the total CO emission (and presumably the H_2 mass) coincides with the compact double nucleus region.

Detailed modeling of the CO line profiles in Arp 220 using a Doppler image-deconvolution technique similar to that used previously for NGC 1068 (Scoville *et al.* 1983) yields a best-fit CO emissivity distribution and rotation curve which are mutually consistent– in the sense that if the total mass distribution follows the CO emissivity, it produces the derived rotation curve. The implied CO-to-H_2 conversion ratio is 0.45 times the Galactic value if the bulk of the mass resides in the molecular gas rather than the stars. The total molecular gas mass for Arp 220 is then inferred to be approximately $\sim 9 \times 10^9\,M_{\odot}$. An important result of the line profile modelling is that the intrinsic velocity dispersion in the extended disk is only $90\,\mathrm{km\,s^{-1}}$. Assuming that the disk gas is entirely self-gravitating, its thickness (FWHM) is only 16 pc. The mean density in this disk is then $2 \times 10^4\,\mathrm{cm^{-3}}$, a value which is entirely consistent with the strong emission from high dipole moment molecules such as HCN and HCO^+ (cf. Solomon *et al.* 1992). If the gaseous disk is only partially self-gravitating, i.e. the potential is dominated by a stellar disk, then the gas thickness can be a few times larger.

¿From the high brightness temperatures of the observed CO emission (17-21 K) and comparison with the infrared color temperature, it is clear that the area filling factor of the disk is very high (~ 0.25), and therefore that the gas must fairly uniformly fill the disk rather than exist in discrete, self-gravitating clouds. This represents a major change in our picture of the central gas distributions in merging galaxies: even in these highly disturbed

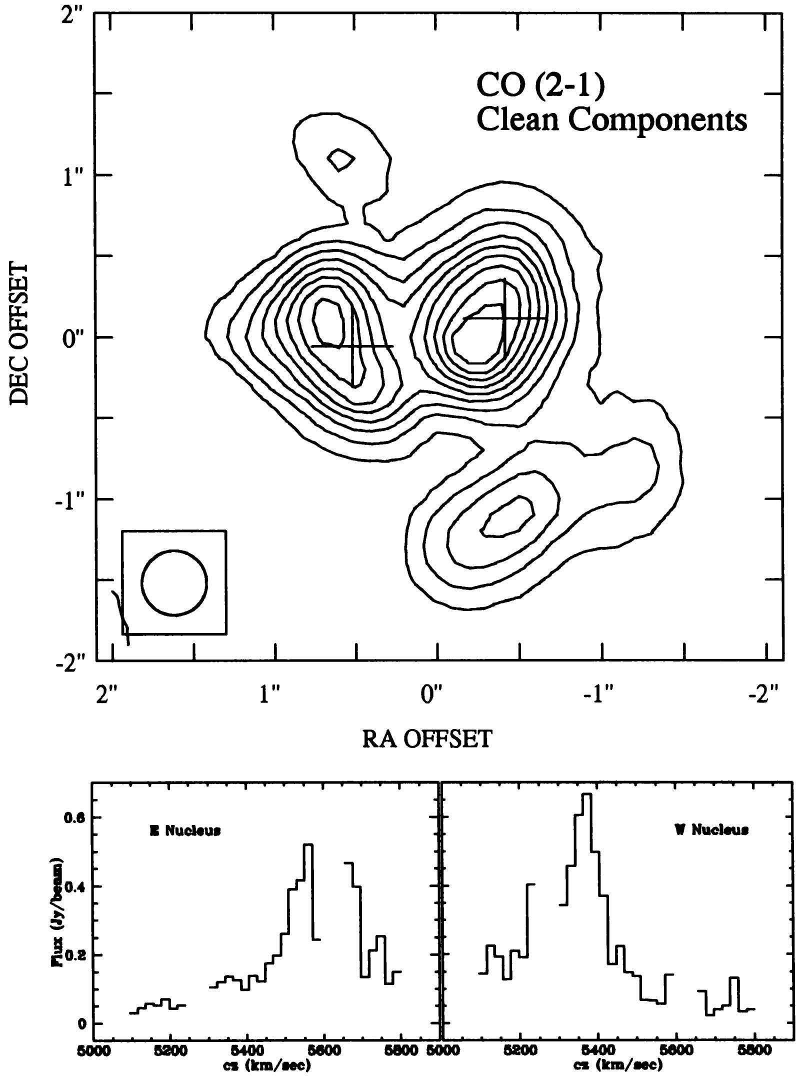

Figure 3. The integrated intensity of CO(2–1) emission from the brightest 'clean' components (Scoville *et al.* 1997b) is shown with the crosses indicating the positions of the two radio nuclei (Baan and Haschick 1992). Spectra of the clean components at the two nuclei are shown at the bottom. Their double horned shapes suggest gas disks within each of the nuclei.

systems, the gas has relaxed to a rotationally supported disk which, due to its extremely high surface density and relatively low velocity dispersion, must be very thin. Presumably, this rapid relaxation has occurred as a result of the very strong dissipation in the interstellar gas. Direct observational evidence for the existence of a thin disk in the center of Arp 220 has recently been provided by high resolution near-infrared imaging obtained with the NICMOS camera on the HST (Scoville *et al.* 1998). The near-infrared images clearly show the dominant western nucleus to be crescent-shaped, as though the central star cluster has been partially obscured by an embedded, opaque dust disk.

Acknowledgments

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